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MODEL FORMULATION OF NON-EQUILIBRIUM GAS RADIATION FOR HYPERSONIC FLIGHT VEHICLES

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ABSTRACT

Several radiation models for low density nonequilibrium hypersonic flow are studied in this report. It is proposed that these models should be tested by the 3-D VRFL code developed at NASA/JSC. A modified and optimized radiation model may be obtained from the testing. Then, the current VRFL code could be expanded to solve hypersonic flow problems with nonequilibrium thermal radiation.

INTRODUCTION

When hypersonic flight vehicles, such as Aeroassisted Orbiter Transfer Vehicles (AOTVS), traveling in low density environment, strong bow shocks occur adjacent to the vehicles. Behind the shock front, the flow involved could be at thermal and chemical nonequilibrium. At the extreme high temperatures, the effect of nonequilibrium gas radiation may be prominent. Determining the magnitude of radiation in this environment is considered to be one of the most important problems associated with AOTVS (1-3).

There are many research works dealing with thermal and chemical nonequilibrium hypersonic flow, some of the recent papers are given in the references (4-10). Although the nonequilibrium radiation is part of the nonequilibrium precesses, it is usually assumed as equilibrium radiation or neglected completely in the analysis. The relatively few work in nonequilibrium radiation research will be mentioned in the later sections.

The purpose of this report is to give a brief discussion of nonequilibrium radiation in low density hypersonic flow, with various models for radiative interaction, numerical solution methods, and some of the available codes. In the next section, the solution methods used for the general nonequilibrium hypersonic flow will be discussed, this is followed by the section dealing with radiation.

THERMAL AND CHEMICAL NONEQUILIBRIUM HYPERSONIC FLOW

There are several numerical methods which can be used for the nonequilibrium hypersonic flow (11). The Direct Simulation Monte Carlo method (12,13), based on probabilistic collision model, requires excessive amount of computer time to solve a two - dimensional flow problem so it may be not able to solve a three - dimensional flow problem. The Viscous shock Layer method (14, 15), which used the simplified conservation equations in the shock

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layer, fails to predict the flow for the whole vehicle. To solve the complete flow field around a hypersonic vehicle, the full Navier stokes equations should be used.

Full Navier-Stokes Equations

In order to calculate radiation from the nonequilibrium region of the flow, one needs to know the thermal and chemical state of th gas in the region. This includes the nonequilibrium species concentrations and various temperatures to express the different energy modes of the species. These state variables can be calculated by simultaneously solving a set of mass, momentum, and energy conservation equations, the so-called full Navier - Stoke equations (2,16,17). The equations consist of one mass conservation equation for each species, one overall momentum equation, and several energy equations. The number of energy equations should equal to the number of temperatures which characterize the various energy modes of the species. For example, when using a two-temperature model of one electron temperature and one heavy-particles temperature, the two energy equations could be one electron energy conservation equation and one overall energy conservation equation. If the two-temperature model used involving one electron-vibrational temperature and one rotational-translational temperature, the two energy equations could be one electon-vibrational energy conservation equation and one overall energy conservation equation. For a three-temperature model of an electron temperature, a vibrational temperature for all species, and a translational-rotational temperature for all species, then there are three energy conservation equations for them. In the literature, the thermal nonequilibrium model could involve more than three temperatures (18), then the computational time has to increase greatly.

In the overall energy equation, there is a term represents the contribution of thermal radiation. This term is expressed by a divergence of a radiation heat flux vector. To evaluate this radiation heat flux vector, a radiative transport equation is needed. The coupling of these equations makes the nonequilibrium flow problem very difficult to solve. The radiative transport equation is discussed in the later section.

Rate Equations

To formulate the full Navier-Stokes equations for nonequilibrium flow, various rate expressions for source functions should be specified. In the mass conservation equation for each species, the source term is the mass production rate of species due to chemical reactions. The chemical reaction rate is a function of the various temperatures used for species. In the energy equation involving translational - vibrational energy exchange, the relaxation time in the rate equation is of the Landau - Teller type (2,17). For the electron-vibrational energy exchange, the relaxation time expression is a modification of the Landau-Teller expression (2,19).

NONEQUILIBRIUM GAS RADIATION

As mentioned in the earlier section, to include a radiation energy term in the overall energy equation, an additional equation is needed, this is the equation of radiative transfer. The coupling between this radiative transfer equation and the energy equation in gas dynamics is of a complicated integral-differential form. When nonequilibrium requirement is included, it adds more complexity to the problem. In the following sections, the basic equation, various simplication and solution methods are briefly discussed.

The Equation of Radiative Transfer

The equation of radiative transfer is a continuity equation for the number density of photons in a specific solid angle and at a specific frequency (17). The equation can be formulated in terms of intensity, emission and absorption coefficients. In a nonequilibrium environment, a knowledge of the emission and absorption coefficients is a requisite to a careful solution of the equation of transfer. The discussion of various spectral models for emission and absorption coefficients is in the next section. since the radiation transport is coupled with flow equations, for a formal solution procedure, one must rely on an iterative method to solve the system of flow equations with radiation transport.

Radiation Transport Models

There are a number of spectral models for radiative interaction computations in the literature. These models are briefly outlined in the following:

<u>Line By Line Transport Calculation</u> Park, etc (3,20,21) has developed a model to calculate radiative properties for nonequilibrium air. the model assumes that the radiation transport is not strongly coupled with the flow equations, so the heavy-particle translational temperature, vibrational temperature, electron temperature, and species mole fractions are solved independently from flow equations. These items will be used as inputs to calculate the number densities of internal state of atoms and molecules by using the so called quasisteady-state assumption. A detailed line-by-line calculation is performed to

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evaluate emission and absorption characteristics independently, using the calculated, nonequilibrium, excited internal state density values. This model requires a tremendous amount of computer time and memory space for the required computations. It becomes even more so when four vibrational temperatures were used for the gas (18). It is very difficult to apply this model to a general 3-D hypersonic flow problem.

The step-Function Absorption Coefficient Model A step function model has been developed to compute the radiation absorption coefficients by Zoby, Sutton, etc. (22). In general, the model includes, free-free, bound-free, and bound-bound transitions of various atoms and molecules. The inputs to the model are species number density and temperature of the flow field. The frequency dependence of the absorption coefficient is represented by a set of steps, these steps has a fixed, but not necessarily equal widths chosen to resolve the detailed spectra adequately. The total absorption coefficient of a particular step is a summation of all the average absorption coefficient of individual energy transitions in that step. The average absorption coefficient of an individual transition can be obtained by integration the absorption coefficient over frequency in that step. When the step width is properly chosen, there should be analytic expressions to approximate the absorption coefficient in that step for the purpose of integration. Thus the frequency dependence for each step becomes a set value, and the total absorption coefficient for that step can now be expressed in terms of species number density and temperature. When this is done, the radiative transfer equation is well expressed in each frequency step. In Reference 22, a 58 steps were used to cover the frequency range from 0 to 17 ev.

Although this model is mainly applied to equilibrium radiation, it includes the frequency dependent absorption coefficient (22,23,24). In addition, with some modifications, this method can be applied to nonequilibrium radiation (25).

There is a similiar but simpler approximation called the band approximation model for absorption coefficient (26,27). This model is also for equilibrium raidation and usually is a two-band approximation model.

Parametric Radiation Model The nonequilibrium radiation environment corresponds to conditions where population densities of the energy levels deviate from the equalibrium Boltzmann distributions based on a single temperature. At sufficiently low densities, the probability of a radiative transition becomes comparable with the probability of a corresponding collisional transition. Unless the gas is optically thick, the emission of a photon is not balanced by its inverse. Consequently, the population distribution among the energy levels departs from the predicted by the Boltzmann equation (25,28). In the formulation of the radiative transfer equation, Tiwari, etc. (25,29) devised a model that the absorption coefficient of different species is calculated by using the 58-step absorption model developed by Sutton (22), while the major nonequilibrium effect will enter through the source function in the equation. For a multilevel energy transitions model, this is done by introducing a parameter n which represents the ratio of the collisional relaxation time and the radiative lifetime of the first excited state, and the higher level energy transitions can be related to this parameter. The nonequilibrium radiation become important for conditions when n = O (1). The key to this model is the determination of collisional relaxation time between various particles and radiative lifetime of the excited states. Additional comparison and analysis are needed for this model.

<u>Other Radiation Models</u> There are a number of other radiation models in the literatures (30-32). Further investigations and testings are needed for these models. In the field of nonequilibrium hypersonic flow with thermal radiation, it is desirable to have more theoretical analysis, computational code developments, and experimental data collections.

Integration of Transfer Equation

To obtain the radiant heat flux vector in the energy equation, the radiative transfer equation needed to be integrated spectrally as well as spatially. This is very difficult to perform on a flow field over a whole vehicle. For an approximation, the tangent slab approximation technique is commonly used (20,22,23,29). This approximation implies that the radiative energy transfer along the body is negligible in comparison to that transferred in the direction normal to the body. Other approximation such as optical thin or/and optical thick assumptions may also be used to solve the problem (18). In general, additional works are needed in the area of fast spatial integration of transfer equation.

CONCLUSIONS

Several radiation models were found in the literature servey. These models need to be tested by some existing 3-D Novier-stokes computer codes. It is proposed that the VRFL code is used for this purpose (7). From the result of testing, comparisons can be made on accuracy of prediction, requirement of computer time and memory space, and generality of the model. To save computer time and to facilitate easy implementation, these models should be

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simplified but retained their essential features. In the computer tests, the flow field may be limited to the stagnation region of a symmetric blunt body for tangent slab approximation, use minimum number of temperatures for thermal model, and assume radiation heat transfer equation and gas dynamic equations are uncoupled. From this testing and additional analysis, a modified and optimized radiation model may be obtained.

After the optimized radiation model is incorporated into the VRFL code, the heat transfer rate to a entire hypersonic vehicle should be calculated. The radiation heat transfer equation and gas dynamic equations are still uncoupled but the tangent slab approximation is removed. The purpose of this test is to find a numerical model for the spatial integration of the radiative transfer equation.

Finally, the expanded VRFL code can be applied to vehicles such as AOTVs. For these computations, the coupling of radiation and gas dynamics should be maintained. The purpose of calculation is not only to accurately predict the heat transfer to the vehicle, but also to find the effect of radiation to the hypersonic flow field.

New radiation model and numerical solution technique may still need to be developed. At present there are still too many unanswered questions in the field of nonequilibrium hypersonic flow with thermal radiation.

REFERENCES

1. Park, C., "Radiation Enhancement by Nonequilibrium in Earth's Atmosphere," AIAA Paper 83-0410, AIAA 21st Aerospace Sciences Meeting, Reno, Nevada, Jan. 1983.

2. Lee, Jong-Hun, "Basic Governing Equations for the Flight Regimes of Aeroassisted Orbital Transfer Vehicles," Thermal Design of Aeroassisted Orbital Transfer Vehicles, ed. by H. F. Nelson, Progress in Astronautics and Aeronautics, vol.96, 1985.

3. Park, C., "calculation of Nonequilibrium Radiation in the Flight Regimes of Aeroassist Orbital Transfer Vehicles," Thermal Design of Aeroassisted Orbital Transfer Vehicles, ed. by H.F. Nelson, Progress in Astronautics and Aeronautics, vol. 96, 1985.

4. Cupta, R.N., Simmonds, A.L., " stagnation Flowfield Anlaysis for an Aeroassist Flight Experiment Vehicle," AIAA paper 88-2613, AIAA Thermophysics, Plasmadynamics and Lasers Conference, San Antonio, Texas, Jun. 1988.

5. Li, C. P., Wey, T. C., "Numerical Simulation of Hypersonic Flow Over an Aeroassist Flight Experiment Vehicle," AIAA paper 88-2675, AIAA Thermophysics, Plasmadynamics and Lasers Conference, San Antonio, Texas, Jun. 1988

6. Li, C. P., "Computation of Three-Dimensional Flow about Aerobrake Configurations," AIAA paper 86-0566, AIAA 24th Aerospace Sciences Meeting, Reno, NV., Jan. 1986.

7. Li, C. P.. "Chemical Nonequilibrium and Viscous Flow Computation for Conic Aerobrake Bodies," Proceedings of ISCFD, Sydney, Australia, Aug. 1987.

8. Li, C. P., "Chemistry-Split Techniques for viscous Reactive Blunt Body Flow computations," AIAA paper 87-0282, AIAA 25th Aerospace Sciences Meeting, Reno, NV, Jan. 1987.

9. Prabhu, D. K., Tannehill, J. C., Marvin, J. G., "A New PNS code for Chemical Nonequilibrium Flows," AIAA paper 87-0248, Jan. 1987.

10. Zoby, E. V., Lee, K. P., Gupta, R.N., Thompson, R. A., Simmonds, A. L., "Viscous Shock-Layer Solutions with Nonequilibrium chemistry for Hypersonic Flows Past Slender Bodies," AIAA paper 88-2709, AIAA Thermophysics, Plasmadynamics and Lasers Conference, San Antonio, Texas, Jun. 1988.

11. Tam, L. T., "A Status Report on Radiation and Thermal Nonequilibrium Modeling for AFE Flowfields," Status Report NAS9-17900, Lockheed Engineering and Management Services Company, Inc., Houston, Texas, May 1988.

12. Moss, J.N., Bird, G. A., "Direct Simulation of Transitional Flow for Hypersonic Reentry condition," Thermal Design of Aeroassisted Orbital Transfer Vehicles, Progress in Astronautics and Aeronautics, vol. 96, ed. by H. F. Nelson, 1985.

13. Moss, J.N., Bird, G. A., Dogra, V. K., "Nonequilibrium Thermal Radiation for an Aeroassist Flight Experiment Vehicle," AIAA paper 88-0081, AIAA 26th Aerospace Sciences Meeting, Reno, NV., Jan. 1988.

14. Song, D. J., Swaminathan, S., Lewis, C. H., "High Altitude Effects on Three-Dimensional Nonequilibrium Viscous Shock-Layer Flows," AIAA paper 84-0304, AIAA 22nd Aerospace Sciences Meeting, Neno, NV., Jan. 1984.

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15. Cheng, H. K., Wong, E., "Flud Dyanmic Modelling and Numerical Simulation of Low-Density Hypesonic Flows," AIAA Paper 88-2731, AIAA Thermophysics, Plasmadynamics and Laser Conference, San Antonio, Texas, June 1988.

16. Appleton, J. P., Bray, K. N. C., "The Conservation Equation for a Nonequilibrium Plasma," J. of Fluid Mechanics, vol. 20, Dec. 1964.

17. Vincenti, W. G., Kruger, Jr. C. H., "Introduction to Physical Gas Dynamics," John Wiley & Sons, New York, 1965.

18. Candler, G., Park, C., "The Computation of Radiation from Nonequilibrium Hypersonic Flows," AIAA paper 88-2678, AIAA Thermophysics, Plasmadynamics and Lasers Conference, San Antonio, Texas, June 1988.

19. Katsuhisa, K., "Electron and Vibrational Energy Conservation Equations for Aeroassisted Orbital Transfer Vehicles," AIAA Journal, Jan. 1987.

20. Arnold, J. O., Cooper, D. M., Park, C., Prekash, S. G., "Line-By-Line Transport Calculations for Jupiter Entry Probes," Entry Heating and Thermal Protection, ed. by W. G. Olstad, Progess in Astronautics and Aeronautics, vol. 69, 1980.

21. Park, C., "Modeling of Radiative Heating in Base Region of Jovian Entry Probe," Entry Heating and Thermal Protection, ed. by W. G. Ostad, Progress in Astronautics and Aeronautics, vol. 69, 1980.

22. Zoby, E. V., Sutton, K., Olstad, W. B., Moss, J. N., "Approximation Inviscid Radiating Flowfield Analysis for Outer Planet Entry Probes," Progress in Astronautics and Aeronautics, vol. 64, 1979.

23. Tiwari, S. N., Szema, K. Y., "Influence of Precursor Heating on Viscous Flow Around a Jovian Entry Body," Progress in Astronautics and Aeronautics, vol. 64, 1979.

24. Sutton, K., "Air Radiation Revisited," Progress in Astronautics and Aeronautics, vol. 96, 1985.

25. Tiwari, S. N., Subramanian, S. V., "Nonequilibrium Radiative Heating of a Jovian Entry Body," Entry Heating and Thermal Protection, ed. by Olstad, Progress in Astronautics and Aeronautics, vol. 69, 1980.

26. Kumar, G. N., Vachon, R. I., "Radiation and Convection Heat Transfer Interactions in the Three Dimensional Compressible Hypersonic Tubulent Boundary on a sharp Cone at an Angle of Attack," Thermal Sciences 16, vol. 1, Hemisphere Publishing Corp., New York, 1983.

27. Kumar, G. N., Vachon, R. I., "Comparision of Three Radiative Formulations for Interactions in Three Dimensional Boundary Layers," AIAA Journal, vol 23, No. 1 Aug. 1984.

28. McWhirter, R. W. P., "Spectral Intensities," Plasma Diagnostic Techniques, ed. by R.H. Huddlestone, etc., Academic Press, New York, 1965.

29. Tiwari, S. N., Subramanian, S. V., "Nonequilibrium Radiative Heating of an ablating Jovian Entry Probe," AIAA Journal, vol 21, Sept. 1983.

30. Carlson, L. A., "Approximations for Hypervelocity Nonequilibrium Radiating, Reacting, and Conducting Stagnation Regions," AIAA Paper 88-2672, AIAA Thermophysics, Plasmadynamics and Lasers Conference, San Antonio, Texas, June 1988.

31. Carlson, L. A., Bobskill, G. J., Greendyde, R. B., "Comparison of Vibration, Dissociation Coupling and Radiative Heat Transfer Models for AOTV/AFE Flowfields," AIAA Paper 88-2673, AIAA Thermophysics, Plasmadynamics and Lasers Conference, San Antonio, Texas June 1988.

32. Babikian, D. S., Edwards, D. K., "Radiation Heat Transfer in the Wake of a Hypersonic Vehicle, "AIAA Paper 88-2634, AIAA Thermophysics, Plasmadynamics and Lasers Conference, San Antonio, Texas, June 1988